COMPACT, DEEP-PENETRATING GEOTHERMAL HEAT FLOW INSTRUMENTATION FOR LUNAR LANDERS S. Nagihara[1], K. Zacny[2], M. Hedlund[2], and P. T. Taylor[3], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Honeybee Robotics, Pasadena, CA 91103, [3]Goddard Space Flight Center, Greenbelt, MD 20711.

Introduction: Geothermal heat flow is obtained as a product of the two separate measurements of geothermal gradient in, and thermal conductivity of, the vertical soil/rock/regolith interval penetrated by the instrument. Heat flow measurements are a high priority for the geophysical network missions to the Moon recommended by the latest Decadal Survey [1] and previously the International Lunar Network [2]. The two lunar-landing missions planned later this decade by JAXA [3] and ESA [4] also consider geothermal measurements a priority.

One of the difficulties associated with heat flow measurement on the Moon is that it requires excavation of a relatively deep (~3 m) hole in order to avoid the long-term changes in lunar surface thermal environment affecting the subsurface temperature measurements [2]. Such changes may be due to the 18.6-year-cylcle lunar precession [5, 6], or may be initiated by presence of the lander itself [7]. Therefore, a key science requirement for a lunar heat flow instrument for the future lunar missions is to penetrate 3 m into the regolith and to measure both thermal gradient and thermal conductivity. Engineering requirements are that the instrument itself has minimal impact on the subsurface thermal regime and that it must be a low-mass and low-power system like any other science instrumentation on planetary landers. It would probably be impossible to meet the engineering requirements, if the instrument utilizes a long probe driven into the ground by a rotary or percussive drill.

Here we report progress in the authors' effort to develop a new, compact lunar heat flow instrumentation that meets all of these science and engineering requirements.

The Proboscis Excavation System: The recently developed 'proboscis' excavation system [8] can largely meet the low-power, low-mass, and the depth requirements. The excavation system utilizes a stem which winds out of a pneumatically driven reel and pushes its conical tip into the regolith. Simultaneously, gas jets, emitted from the cone tip, loosen and blow away the soil (Fig. 1). In its current design, the stem is primarily made of glass fiber for its mechanical strength and relatively low thermal conductivity. Helium gas is used for the jet, because it is commonly available for planetary landers in pressurizing the propellant tank. Lab tests using an earlier proboscis model in a vacuum chamber have shown that only 8 g of He gas is required for excavating 0.6 m in 22 seconds [9]. The near-vacuum environment of the lunar surface maximizes the mechanical force of the gas jet.

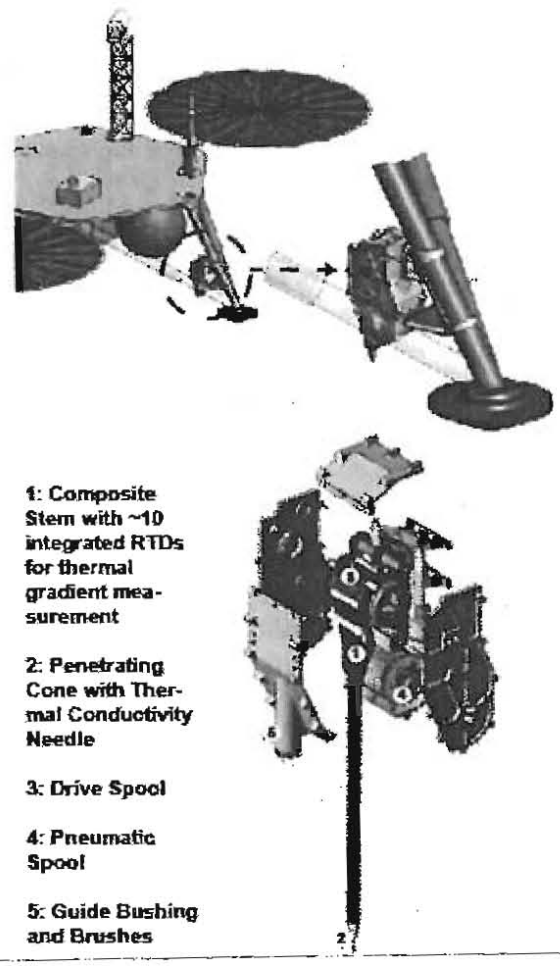

Figure 1: Top: A conceptual drawing of the proposed heat flow instrumentation attached to a leg of a lunar lander. Bottom: More detailed schematics of the major components of the heat flow system.

The *In-situ* Thermal Conductivity Probe Attached to the Proboscis Excavation System: A typical thermal conductivity probe used for terrestrial soil samples (the so-called 'needle probe') consists of a thin metal tube of ~2-mm diameter and ~5-cm length, which contains a linear electric heater along its length and a temperature sensor (e.g., thermistor) at its center. When the probe is inserted into the soil, it heats up and

monitors the temperature increase [10]. The measurement theory requires that the length of the probe is much greater than its diameter and that the probe is made of highly conductive material. In such a configuration, one can assume that the heat diffuses away through the soil dominantly in the radial direction from a line heat source, and that temperature of the probe is always the same as that of the soil in contact with the probe. Then, the thermal conductivity can be an algebraic function of the heat input and the logarithmic rate of the temperature rise:

$$K = \frac{Q}{4\pi} \cdot \frac{d(\ln t)}{dT} \qquad (1)$$

where K is the thermal conductivity, Q is the heat generated per unit length of the probe, T is the temperature, and t is the time.

The thermal conductivity probe for the new heat flow system is attached to the tip of its penetrating cone (Fig. 2). In order not to diminish the excavation efficiency, the probe is short (1-cm). The probe has a diameter of 3-mm in order to insure good thermal contact with powdery regolith materials in vacuum, and for mechanical strength. The penetrating cone in its current design is made of a low-conductivity plastic in order to thermally insulate the probe from the rest of the instrument. The short needle contains a platinum wire-wound resistance temperature detector (RTD), and a thin heater wire which wraps around the cylindrical ceramic casing of the RTD.

During a deployment, when the penetrating cone reaches one of the depths targeted for thermal conductivity measurement, it stops blowing gas, and the stem pushes the short probe into the yet-to-be excavated, undisturbed bottom-hole soil. Then, it begins heating and monitors the temperature rise. When, the measurement is complete, the system resumes excavation.

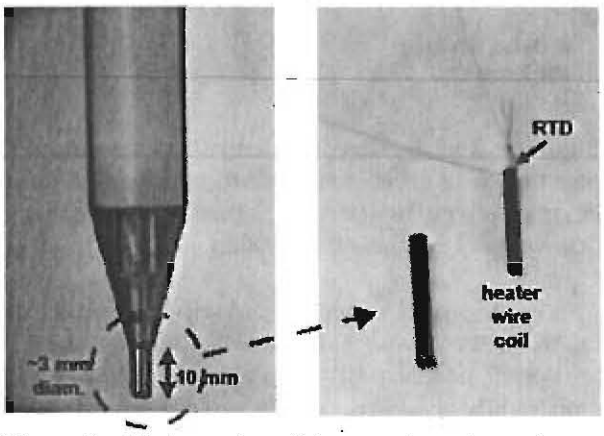

Figure 2: Photographs of the prototype thermal conductivity probe.

Thermal Conductivity Experiments: A prototype of the short thermal conductivity probe (Fig. 2) has been tested with lunar regolith simulant JSC-1A placed in a vacuum chamber for various air pressures. The container of the simulant was large enough to accommodate two probes inserted, ~8 cm apart. One was the new short probe and the other was a standard thermal conductivity probe (*Decagon KD2 Pro*) with 2.4-mm diameter and 10-cm length. The two probes were far enough apart to allow simultaneous heating experiments. Data from the latter probe yielded thermal conductivity of JSC-1A as a function of chamber pressure (Fig. 3).

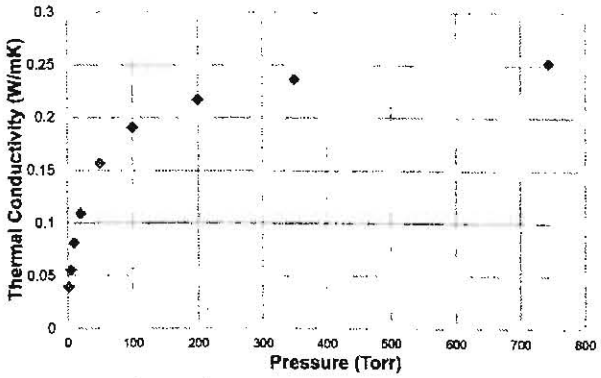

Figure 3: Thermal conductivity of the JSC-1A lunar simulant measured for a range of chamber pressures. The simulant was well compacted before the measurements.

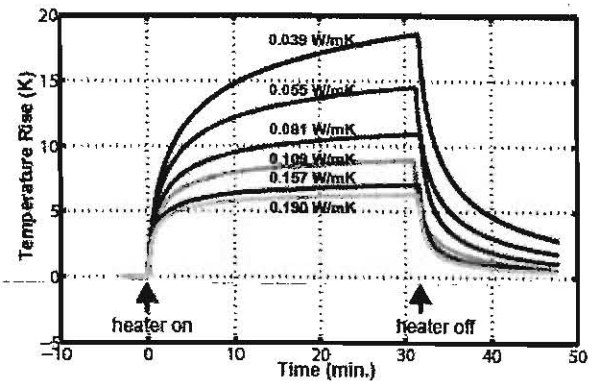

Figure 4: Temperature records from 6 heating tests of the short probe shown in Fig. 2. Each curve represents one test result conducted at a fixed chamber pressure. The thermal conductivity of the regolith at that pressure is noted for each of the curves drawn.

For each set of heating experiments at a fixed pressure, the short probe was heated for 30 minutes (Fig. 4) with a constant power of 50 mW. The length/diameter ratio of the short needle is not large enough to allow direct application of the standard needle probe tech-

nique (Eq. 1). However, it can be seen that, for each heating experiment, there is a linear relationship between the temperature and the natural log of time after ~4 minutes of heating (Fig. 5):

$$T = C \ln t + T_0 \qquad (2)$$

where T_0 is the initial temperature and C is a constant.

If this were for a standard, long needle probe, C is equivalent to $Q/(4\pi K)$. For the short probe, such relationship does not necessarily hold. However, it gives hope that the logarithmic rate of temperature increase (C) for the short probe may be inversely proportional to the thermal conductivity of the medium being measured. In other words, the relationship between these two quantities may be similar to Eq. 1. We have obtained the product of C and the thermal conductivity obtained by the standard probe (K) for each set of experiments (Table 1). The $C{\cdot}K$ values for pressures less than 20 Torr or thermal conductivity values of 0.1 W/mK are remarkably similar. Within the low pressure, low thermal conductivity range, C and K are indeed inversely proportional. Therefore, it is possible to uniquely determine the thermal conductivity of the medium from knowledge of the temperature increase with time, if the $C{\cdot}K$ value has been pre-determined for the probe by a series of calibration experiments.

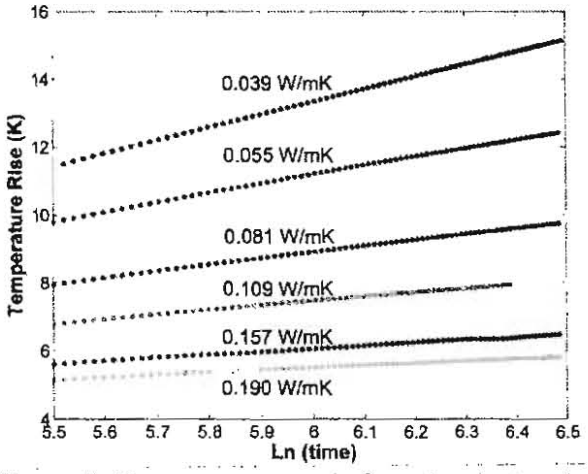

Figure 5: Temperature records from the short probe heating tests replotted in the natural log time scale. Time is in seconds. The slope of each line corresponds to the parameter C described in the text.

Table 1: $C{\cdot}K$ values obtained from the heating tests of the short probe for JSC-1A at different K values.

Pres.	2	5	10	20	50	100
K	0.039	0.055	0.081	0.109	0.157	0.190
$C{\cdot}K$	0.146	0.146	0.147	0.146	0.136	0.126

Units for pressure and thermal conductivity are Torr and W/mK, respectively.

Discussion and Conclusions: In-situ thermal conductivity of lunar regolith has been previously reported to be 0.009 to 0.013 W/mK at Apollo 15 and 17 sites [11]. In our lab experiments, we were not able to lower the chamber pressure below 2 Torr to duplicate the condition on the Moon. It is still noteworthy that, at the lowest thermal conductivity values achieved for the JSC-1A simulant, the short probe yielded the best performance. For thermal conductivities between 0.039 W/mK and 0.109 W/mK, the $C{\cdot}K$ values were constant (Table 1). Within this range, it is possible to obtain the thermal conductivity simply as:

$$K = 0.146 \times \frac{d(\ln t)}{dT} \qquad (3)$$

Given how constant $C{\cdot}K$ is in this range (Table 1), it may be possible to determine thermal conductivity within $\pm$ 0.001 W/mK. Whether or not this relationship holds at lower pressures needs to be test in future studies.

The use of empirically obtained $C{\cdot}K$ is very similar to the approach taken by the investigators of the Apollo Heat Flow Experiments [12]. Their 50-cm long, 2.54-diameter probe was heated only at short (~2.5 cm) sections for thermal conductivity measurements. The conventional line heat source model (Eq. 1) was not applicable. The investigators empirically obtained $C{\cdot}K$ for their probes by carrying out a series of lab experiments.

Prior to the present study, two types of compact *in-situ* thermal conductivity systems were proposed for low-mass lunar robotic missions. One was a button-shaped device containing a heater-RTD assembly, imbedded in the outer casing of a bullet-shaped penetrator (0.8-m length and 0.15-m diameter) dropped from a Lunar-orbiting spacecraft [13]. The other was a heater-RTD assembly built into the casing of a 'mole' self-hammering system deployed from a lander [14, 15].

Either of these previous approaches has difficulty in achieving high accuracy in thermal conductivity measurement, mainly because temperature measured by its RTD is heavily influenced by that of the instrument body to which the sensor is built/attached. The instrument body has a much larger heat capacity and thermal inertia than the temperature sensor itself. The instrument body is 2 or 3 orders of magnitude more thermal conductive than lunar regolith. Therefore, temperature felt by the sensor may be closer to that of the instrument body reacting to the self heating than that of the soil/regolith in contact.

The present design of inserting a small, low-heat-capacity probe into regolith significantly reduces the thermal inertia problem. Also, in this design, the probe is relatively insulated from the rest of the instrument body. This way, the RTD senses the temperature of

the regolith more accurately and responds more quickly to temperature changes. It has further advantage in that the small probe causes less mechanical disturbance to the regolith than the penetrator (free-falling into the regolith) or the mole (hammering and compacting the soil) does. Finally, the small probe does not require as much heater power in making a thermal conductivity measurement, because its heat capacity is much less.

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References: [1] National Research Council (2011) pub# 13117. [2] Cohen, B. A. et al. (2009) ILN Final Report. [3] Tanaka et al. (2012) *LPSC XXXXIII* 1651. [4] ESA Lunar Lander Team (2012) Exploration Science Requirements Document. [5] Wieczorek, M. A. and Huang, S. (2006), *LPSC XXXVII*, 1682. [6] Saito, Y. et al. (2006), *Bull. Japanese Soc. Planet. Sc. 16*, 158-164. [7] Kiefer, W.S. (2011) Planet Space Sc., 60, 155-165. [8] Zacny, K. et al. (2011) *LEAG* 2028. [9] Zacny et al. (2009) *LPSC XXXX* 1070. [10] Beardsmore, G. R. and Cull, J. P. (2001) *Crustal Heat Flow*, Cambridge Univ. Press. [11] Langseth et al. (1976) *LPSC VII* 3143-3171. [12] Langset et al. (1972) *Apollo 15 Prelim. Sc. Rep.* 11-1 – 11-20. [13] Mizutani et al. (2003), *Adv. Space Res. 21*, 2315-2321. [14] Seweryn et al. (2008) *LPSC XXXIX* 1957 [15] Spohn et al. (2012) *LPSC XXXXIII* 1445.